1/32° Global Ocean Modeling and Prediction

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Abstract

This DoD HPC Challenge project is a crucial component of an effort to develop a data-assimilative 1/32º global ocean nowcast/forecast system, which includes the associated basic research and exploratory development. The need for 1/32º resolution (~4 km) has been demonstrated through extensive research, including essential contributions from our FY97 and FY98-00 DoD HPC Challenge projects. These projects also helped establish 1/16º (~7 km at mid latitudes) as the minimum resolution needed for a fully eddy-resolving global ocean model. Major improvement was obtained with an increase to 1/32º resolution, but only modest additional improvement with a further increase to 1/64º resolution.

Our previous DoD HPC Challenge projects were a critical component of the effort to develop a 1/16º global ocean nowcast/forecast system. That system has been transitioned to the Naval Oceanographic Office (NAVO) and NAVO has been running it in real time since 18 Oct 2000 with assimilation of altimeter sea surface height (SSH) data from three satellites and sea surface temperature (SST) from satellite IR. It clearly demonstrates the ability to track the evolution of oceanic eddies and the meandering of ocean currents and fronts, which have space scales O(100 km). At least 30-day forecast skill has also been demonstrated globally. Results can be viewed on the web at http://www7320.nrlssc.navy.mil/global_nlom/index.html. An invited case study on our work entitled "Eddy-resolving global ocean modeling and prediction" has been archived in the permanent research collection of the Smithsonian National Museum of American History and is viewable at the web address:
http://www.cwheroes.org/cgi-bin/db_main/db1.pl?fid=981489338.362018&Search&cgifunction=form.

The full resources of a large three-year HPC Challenge project are required to permit 2003 transition of a 1/32° global ocean nowcast/forecast system to NAVO. That includes (a) multi-decade 1/32° global ocean simulations which are needed to assess the realism and dynamics of the model and for the generation of statistics and a model mean SSH needed in the data assimilation, (b) ocean nowcast experiments with data assimilation into the model and (c) ocean forecast experiments initialized from the experiments with data assimilation. So far, we have initialized the 1/32° global model from a spun up 1/16° version and we have run it 19 years with climatological atmospheric forcing. We are on track using our HPC Challenge allocation (which is on the NAVO IBM SMP) and we are nearly ready to start an interannually-forced simulation. The results show major improvement in simulating the Gulf Stream, including a realistic pathway (which was fairly good in the 1/16° model), and a much stronger associated nonlinear recirculation gyre with greater and more realistic eastward penetration. This alters

the large-scale shape of the subtropical gyre. There is also increased eastward penetration of the high variability and well as increased variability in many regions of the world ocean. Both the 1/16° and 1/32° models match the well-known Gulf Stream transport through the Florida Straits within 5%, but the 1/32° model gives a more accurate distribution of the passage transports in the Caribbean/Bahamas/Gulf of Mexico region. The NRL/NAVO global ocean prediction effort is a participant in the multinational Global Ocean Data Assimilation Experiment (GODAE) which is designed to help justify a permanent global ocean observing system by demonstrating useful real-time global ocean products with a customer base. Our effort is represented on the U.S. and International GODAE Steering Teams.

Objectives

This DoD Challenge project is part of a coordinated 6.1-6.4 effort on the "Grand Challenge" problem of eddy-resolving global ocean modeling and prediction. In particular, it is a crucial component of an effort to develop a data-assimilative 1/32° global ocean nowcast/forecast system, doubling the resolution of a 1/16° system already transitioned to NAVO. The long term objectives are to simulate, understand, nowcast and forecast the global ocean circulation, and to increase the capability to model it. Research topics include ocean dynamics, model development and portability to different computer architectures, ocean simulation, model validation, data assimilation, ocean nowcasting and forecasting, observing system simulation, and applications of naval interest. The 1/32° model results offer an unprecedented opportunity for oceanographic research at ~4 km resolution, including regional studies within the context of the global ocean circulation. In addition, the NRL/NAVO global ocean prediction effort is a participant in the multinational Global Ocean Data Assimilation Experiment (GODAE) which is designed to help justify a permanent global ocean observing system by demonstrating useful real-time global ocean products with a customer base (International GODAE Steering Team, 2000). Our effort is represented on the U.S. and International GODAE Steering Teams. GODAE is scheduled for 2003-2007 with pilot programs in 2000-2002.

Applications for the models and the nowcast/forecast systems include assimilation and synthesis of global satellite surface data; ocean prediction; optimum track ship routing; search and rescue; anti-submarine warfare and surveillance; tactical planning; high resolution boundary conditions that are essential for even higher resolution coastal models; inputs to ice, atmospheric and bio-physical models and shipboard environmental products; environmental simulation and synthetic environments; observing system simulations; ocean research; pollution and tracer tracking and inputs to water quality assessment. Assimilation of satellite altimeter data into the models makes more effective use of near real-time altimeter data from the Navy's Geosat Follow On (GFO) mission, TOPEX/POSEIDON and ERS-2 via NAVO's Altimeter Data Fusion Center (ADFC). Sea surface temperature (SST) and other data will be assimilated as well.

Resolution Requirements for Ocean Modeling

A critical issue in forecast system design is determining the resolution required. Ocean models require finer resolution and more computer time than atmospheric models in part because the space scales for variability due to flow instabilities (oceanic mesoscale eddies vs. atmospheric highs and lows) are about 20-30 times smaller than found in the atmosphere. We need to resolve the oceanic eddy space scale very well because (1) it is relevant for most of the Navy applications listed earlier, (2) these models need to provide high resolution boundary conditions for even higher resolution coastal models, (3) upper ocean – topographic coupling via flow instabilities has a major impact on the pathways of many upper ocean currents (including mean pathways) and very fine resolution of the flow instabilities is required to get sufficient coupling (Hurlburt, et al., 1996; Hurlburt and Metzger, 1998; Hogan and Hurlburt, 2000), (4) very fine resolution is required to obtain (a) inertial jets and sharp oceanic fronts which span major ocean basins as observed (Hurlburt, et al., 1996) and (b) the associated nonlinear recirculation gyres which affect the shape of large-scale ocean gyres (Hurlburt and Hogan, 2000), (5) it is necessary to resolve small islands and narrow passages which affect current pathways and current transports in many regions (e.g. Metzger and Hurlburt, 2001), (6) in data assimilative mode we do not want the ocean model to "fight" the data because the natural behavior of the ocean model is inconsistent with the observations (Hurlburt, et al., 2000), and (7) a very high horizontal resolution model is needed to help get an accurate mean sea surface height field to add to the deviations obtained from satellite altimetry (observations alone do not provide sufficient resolution to do this).

The need for 1/32° resolution (~4 km) has been demonstrated through extensive research, including essential contributions from our FY97 and FY98-00 DoD HPC Challenge projects as well as non-challenge HPC usage (e.g. the publications cited above). These projects also helped establish 1/16° (~7 km at mid latitudes) as the minimum resolution needed for a fully eddy-resolving global ocean prediction system. Major improvement in model simulation skill was obtained with an increase to 1/32° resolution, but only modest additional improvement with a further increase to 1/64° resolution (Hogan and Hurlburt, 2000; Hurlburt and Hogan, 2000).

Earlier Transition of a 1/16° Global Ocean Prediction System to NAVO

Our previous DoD HPC Challenge Projects were a critical component of the effort to develop the world's first eddy-resolving global ocean nowcast/forecast system at the minimum (1/16°) resolution needed for a fully eddy-resolving system. The 1/16° global system has been transitioned to NAVO and NAVO has been running it in real-time since 18 Oct 2000. It assimilates real-time satellite altimeter SSH data (currently GFO, TOPEX and ERS-2) that is available from NAVO's Altimeter Data Fusion Center (ADFC) as well as SSTs from satellite IR. The nowcasts are updated daily and 30-day forecasts are made every Wednesday. The system gives a real-time view of the ocean down to the 50-200 km scale of ocean eddies and the meandering of ocean currents and fronts. At least 30-day forecast skill has been demonstrated globally, including fronts and eddies and many other ocean features. Real-time and archived results from the system can be viewed on the internet at the NRL web address:
http://www7320.nrlssc.navy.mil/global_nlom/index.html.
This includes nowcasts, forecasts and forecast verification statistics for many subregions plus comparisons between the nowcasts and unassimilated SST time series and temperature profiles from moored buoys. An invited case study on our work entitled "Eddy-resolving global ocean modeling and

prediction" (Hurlburt and Wallcraft, 2000) has been archived in the permanent research collection of the Smithsonian National Museum of American History and is viewable at the web address: http://www.cwheroes.org/cgi-bin/db_main/db1.pl?fid=981489338.362018&Search&cgifunction=form.

Approach and Planned Research

Global ocean modeling and prediction is one of the original grand Challenge problems that, by definition, require a Tflop/s (sustained) performance. NRL's approach to this problem seeks to reduce the cost via a careful choice of algorithms and the use of a Lagrangian vertical coordinate. Because the NRL Layered Ocean Model (NLOM) has a factor of 10s-100s advantage in computer time requirements over other global and basin-scale ocean models, we can "solve" this problem on a computer sustaining O(100) Gflop/s. The NRL modeling strategy is discussed in the Hurlburt and Wallcraft (2000) case study for the Smithsonian, which uses the case studies as one means of developing a history of information technology and its benefits to society. NLOM (Wallcraft, 1991; Wallcraft and Moore, 1997) is written in the tiled data parallel programming style. It is scalable using: (a) autotasking, or (b) data parallel Fortran, or (c) SHMEM library calls, or (d) Message Passing Interface (MPI) library calls and thus is portable to a wide variety of computing platforms.

The 1/32° global ocean prediction system represents a doubling of the resolution and an 8-fold increase in computer time requirements over the 1/16° global system transitioned to NAVO in 2000. Therefore, the full resources of a large three-year HPC Challenge project are required to permit transition of a 1/32° global system to NAVO in 2003. In the first step climatological atmospheric forcing is used to extend the equilibrated 1/16° global model at 1/32° resolution until it is nearly re-equilibrated, a step that is almost complete as of June 2001. In addition to re-equilibration, the climatological simulation is used to fix problems that arise, optimize model parameters, assess the impact of the resolution increase on model realism and dynamics and to perform climatological model-data comparisons.

The climatological simulation will be followed by (1) simulations forced interannually by two different atmospheric products, (2) ocean nowcast experiments with data assimilation into the model, and (3) ocean forecast experiments initialized from the experiments with data assimilation. Two simulations with ECMWF atmospheric forcing will be integrated from 1979-2002 using the 6-hourly ECMWF reanalysis 1979-1993 and 12-hourly archived operational forcing 1994-2002. The ECMWF product is widely acknowledged as the best available and is available over an interval long enough to include a wide range of variability. In particular it extends back far enough to include the 1982-83 El Niño (with some lead-time), an El Niño which had at least a decadal impact on Pacific Ocean variability (Jacobs et. al., 1994). It also provides an excellent benchmark for comparison with the simulations atmospherically forced by the Navy's 12-hourly NOGAPS product from FNMOC. In all of the interannual runs the temporal mean of the wind forcing will be replaced by the annual mean from the Hellerman and Rosenstein (1983) (HR) wind stress climatology used to force the climatologically forced simulation. This minimizes additional spin-up effects when the interannual forcing is started and it avoids the need for separate spin-ups for different wind products. Overall, HR wind stress forcing gives the most realistic model means of the wind products we have tried.

The ECMWF forced simulations will be used to assess the model realism and dynamics in representing atmospherically forced variability on a wide range of time and space scales and dynamical regimes. The two simulations will be identical except that they will be started from different years of the climatological spin-up. Identical twin simulations are needed to investigate deterministic vs. nondeterministic ocean model responses to the atmospheric forcing and the relative importance of each as a function of region and ocean phenomena, a distinction which has application for data assimilation, ocean forecasting, ocean dynamics and model-data comparisons. The interannual simulations are critical for comparisons to data sets taken over specific time frames. They also help us investigate the model's ability to produce a wide range of oceanic variability. In addition, interannual simulations attract greater interest from researchers outside of NRL. The 1/32° model resolution is an unprecedented opportunity to study regional oceanography and dynamics at high resolution in the context of the global ocean circulation (which is also influenced by the high resolution). Major scientific objectives include investigating (a) the interactions between the thermohaline component of the circulation, the wind-driven component and the mesoscale eddy field; (b) the influence of upper ocean – topographic coupling via baroclinic instability on the preceding and on the pathways of upper ocean currents; (c) the influence of the global ocean circulation on regional dynamics; and (d) Low Latitude Western Boundary Currents (LLWBCs) and their roles in interbasin exchange.

The FNMOC NOGAPS forced simulations would be integrated 1990-near real time starting from an ECMWF forced simulation. The two FNMOC NOGAPS forced simulations will not be identical twins, but instead a first attempt and an improved second attempt. All of the data assimilation experiments will be initialized from the FNMOC NOGAPS forced simulations and will use this forcing during data assimilation and forecasting experiments except for forecasting experiments where the atmospheric forcing is relaxed towards climatology during the forecast. This will be done to assess the impact of atmospheric forcing on oceanic forecast skill as a function of time, region and dynamical regime. In addition to comparison with the ECMWF-forced simulations, the FNMOC forced simulations will be compared with data-assimilative runs to assess the impact of the data assimilation. In all cases these comparisons will be done in the context of model-data comparisons using contemporaneous data.

The data assimilation experiments will be used to improve and optimize data assimilation techniques at 1/32° over a wide range of ocean regions and dynamical regimes. The interannual simulations will be used to provide statistical parameters for the subsurface statistical inference technique (Hurlburt et. al., 1990) used to project the surface data downward to update the lower layers of the ocean model. They will also provide a high resolution global temporal mean SSH which must be added to the SSH deviations obtained from satellite altimetry. Surface dynamic height from hydrographic climatologies is inadequate for this purpose. NLOM is designed to provide accurate mean sea surface height. It agrees well with the hydrographic climatologies but provides a much sharper depiction of mean currents. More basic data assimilation technique development will be done using lower resolution models, and is not part of this project. However, the ocean model is an integral component of the data assimilation scheme because of the importance of its dynamical interpolation skill and because it provides statistics for the subsurface updates and a mean SSH field to go with the altimetric deviations from the mean. Thus, ultimately, data assimilation improvement, optimization and testing must be done using the 1/32°

global model. This includes assessment of data assimilation skill using forecast skill as a gauge. In addition, the forecast experiments will be used to assess model forecast skill as a function of region and dynamical regime. Finally, two assimilation experiments run from 1993 (the start of TOPEX/POSEIDON altimeter data) up to near real time are planned to assess data assimilation and forecast skill over a wide range of variability in each region. These assimilation runs will allow researchers to follow the evolution of observed oceanic anomalies with unprecedented resolution and with space-time continuity that is generally not possible using raw data.

1/32° Global Ocean Model Results

The 1/32° global ocean model has completed 19 years of the climatological simulation as of mid June 2001. This is the highest resolution to date for a global ocean model. We are on track in using our HPC Challenge allocation, which is on the NAVO IBM SMP. We are nearly ready to start a simulation with 6-hourly interannual forcing which will be initialized from the nearly spun-up climatological simulation. Figure 1 is an SST snapshot from the 1/32° climatological simulation. As discussed by Wallcraft et al. (2000) in last year's HPC paper, NLOM has demonstrated excellent skill in simulating SST with no relaxation to nor assimilation of SST data. Likewise, the SST in figure 1 was simulated using atmospheric forcing alone. SST is assimilated into the real-time 1/16° global ocean nowcast/forecast system. Nowcast SST comparisons with unassimilated buoy time series and SST forecast verification statistics can be seen on the real-time web page given earlier.

Figure 2 shows results from the climatologically-forced 1/32° global model in the Gulf Stream region, one of the most challenging regions to simulate in the world ocean. It also shows comparisons to the corresponding 1/16° climatological global simulation and to observations. The mean SSH and the snapshot are shown in comparison to the 15-year mean northwall of the Gulf Stream from satellite IR (middle line) flanked by lines one standard deviation away. Both models show a realistic mean Gulf Stream pathway, although the 1/16° model has a slight northward bulge near 70°W. Resolution of 1/16° or ~7 km is the minimum required to obtain a realistic Gulf Stream pathway. The pathway is very unrealistic and the Gulf Stream transport is much too weak at coarser resolution. However, a realistic pathway is more easily and robustly obtained at 1/32° resolution and the Gulf Stream transport is much higher and more realistic, particularly south of the Grand Banks between 50°W and 55°W. Associated with this large increase in transport is a large increase in the strength and eastward penetration of the nonlinear recirculation gyre on the south side of the Gulf Stream (shown in red and black). This alters the large-scale C-shape of the subtropical gyre.

The SSH snapshot shows the meandering of the Gulf Stream with eddies on both sides, including many well away from the Gulf Stream. Figure 2 also shows a comparison of SSH variability in the Gulf Stream region from the 1/16° and 1/32° global models and from Topex/Poseidon altimeter data. It should be noted that the variability from Topex/Poseidon looks somewhat smeared and blobby because of the coarse spacing of the altimeter tracks with local maxima at the track locations. The pattern and amplitude of the variability reveals valuable information about the models' ability to simulate specific features of the flow field. In the 1/32° model the high variability extends farther to the east and matches the pattern and amplitude from Topex/Poseidon much better. However, the northeastward extension of variability between 40°W and 47°W is too weak in both models, although it is still a region of high model variability in comparison to most ocean regions. Starting from west to east, all three show the narrow band of very high variability west of 68°W and a broadening east of that longitude. There is a local bulge of high variability to the south in the region of the New England Seamont Chain, but the 1/32° model shows better longitudinal agreement with Topex/Poseidon. Between 45°W and 50°W the 1/32° model and Topex/Poseidon show a corridor of high variability wrapping around the nonlinear recirculation gyre, which is lacking in the 1/16° model. This shows that the 1/32° model simulates realistic eastward penetration for the nonlinear recirculation gyre.

The 1/32° global model also shows higher SSH variability then the 1/16° model in many other regions of the world ocean. Even though the SSH variability is much weaker in much of the rest of the world ocean, strong eddies are ubiquitous in most of the world ocean. The SSH signature is just weaker than across the Gulf Stream and in strong cold core rings on the south side of the Gulf Stream. In addition, interannual atmospheric forcing contributes greatly to the SSH variability in much of the world ocean, but is not a major factor in the Gulf Stream region.

Table 1 shows a comparison between the 1/16° and 1/32° models and observed mean passage transports in the Caribbean, Bahamas and Gulf of Mexico region, although only the mean Gulf Stream Transport through the Florida Straits at 27°N is precisely known from observations. Both model means match that transport to within about 5% and both generally show reasonable agreement with the observations, but the 1/32° model shows substantial improvement for Northwest Providence Channel, the Yucatan Channel and Windward Passage. The improvement in Yucatan Channel transport is particularly significant because it feeds the Loop Current which sheds large eddies in the Gulf of Mexico.

Acknowledgements

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References

Atkinson, L.P., T. Berger, P. Hamilton, E. Waddell, K. Leaman and T.N. Lee, 1995: Current meter observations in the Old Bahama Channel, *J. Geophys. Res*., **100** (C5), 8555-8560.

da Silva, A.M., C.C. Young and S. Levitus, 1994: Anomalies of heat and momentum fluxes. Atlas of Surface Marine Data 1994. Vol. 3, NOAA Atlas NESDIS 8, U.S. Dept. of Commerce, NOAA, NESDIS, 413 pp.

Hellerman, S. and M. Rosenstein, 1983: Normal monthly wind stress over the world ocean with error estimates. *J. Phys. Oceanogr*., **13**, 1093-1104.

Hogan, P.J. and H.E. Hurlburt, 2000: Impact of upper ocean – topographic coupling and isopycnal outcropping in Japan/East Sea models with 1/8º to 1/64º resolution, *J. Phys. Oceanogr*., **30**, 2535-2561.

Hurlburt, H.E., D.N. Fox, and E.J. Metzger, 1990: Statistical inference of weakly correlated subthermocline fields from satellite altimeter data. *J. Geophys. Res.*, 95, 11375-11409.

Hurlburt, H.E. , A.J. Wallcraft, W.J. Schmitz Jr., P.J. Hogan, and E.J. Metzger, 1996: Dynamics of the Kuroshio/Oyashio current system using eddy-resolving models of the North Pacific Ocean, *J. Geophys. Res*., **101**, 941-976.

Hurlburt, H.E. and E.J. Metzger, 1998: Bifurcation of the Kuroshio Extension at the Shatsky Rise, *J. Geophys. Res.*, **103**, 7549-7566.

Hurlburt, H.E., R.C. Rhodes, C.N. Barron, E.J. Metzger, O.M. Smedstad, and J.-F. Cayula, 2000: A feasibility demonstration of ocean model eddy-resolving nowcast/forecast skill using satellite altimeter data. NRL/MR/7320--00-8235, Naval Research Laboratory, Stennis Space Center, MS, 23 pp.

Hurlburt, H.E. and A.J. Wallcraft, 2000: Eddy-resolving global ocean modeling and prediction. 2000 Innovation Collection Case Study for the Smithsonian Institution's Permanent Research Collection at http://www.cwheroes.org, 7 pp. (invited and refereed).

Hurlburt, H.E. and P.J. Hogan, 2000: Impact of 1/8º to 1/64º resolution on Gulf Stream model-data comparisons in basin-scale subtropical Atlantic Ocean models, *Dyn. Atmos. Oceans*, **32**, 283-329.

International GODAE Steering Team, 2000: Global Ocean Data Assimilation Experiment Strategic Plan. GODAE Report #6. Published by the GODAE International Project Office, c/- Bureau of Meteorology, Melbourne, Australia, 26pp.

Jacobs, G.A., H.E. Hurlburt, J.C. Kindle, E.J. Metzger, J.L. Mitchell, W.J. Teague and A.J. Wallcraft, 1994: Decadal-scale trans-Pacific propagation and warming effects of an El Nino anomaly. *Nature*, **370**, 360-363.

Johns, W.E., T.L. Townsend, D.M. Fratantoni and W.D. Wilson, 2001: On the Atlantic inflow to the Caribbean Sea, submitted to Deep-Sea Res.

Larsen, J.C. , 1992: Transport and heat flux of the Florida Current at 27ºN derived from cross-stream voltages and profiling data: theory and observations. *Phil. Trans. Roy. Soc. London A*, **338**, 169-236.

Leaman, K.D., P.S. Vertes, T.N. Lee, P. Hamilton and E. Waddell, 1995: Transport, potential vorticity, and current/temperature structure across Northwest Providence and Santaren channels and the Florida Current off Cay Sal Bank, *J. Geophys. Res.*, **100** (C5), 8561-8569.

Lee, H., S.M. Glenn and D.B. Haidvogel, 1997: A Gulf Stream synthetic geoid for the TOPEX altimeter. *J. Atmos. Oceanogr. Tech*. (submitted)

Lee, T.N., W.E. Johns, R.J. Zantopp and E. Fillenbaum, 1996: Moored observations of western boundary current variability and thermohaline circulation at 26.5ºN in the subtropical North Atlantic. *J. Phys. Oceanogr.*, **26**, 962-983.

Metzger, E.J. and H.E. Hurlburt, 2001: The importance of high horizontal resolution and accurate coastline geometry in modeling South China Sea inflow. *Geophys. Res. Letters*, **28**, 1059-1062.

Nelepo, B.A., V.N. Stepanov, R.P. Bulatov and M.M. Donanov, 1976: Soviet investigations of the dynamics and properties of the waters of the Caribbean Sea and Gulf of Mexico, CICAR II, Symp. on Mar. Res. in the Caribbean and Adjacent Regions, Caracas, FAO Fisheries Report 200, 119-131.

Niiler, P.P. and W.S. Richardson, 1973: Seasonal variability of the Florida Current. *J. Mar. Res.*, **31**, 144-167.

Richardson, W.S. and J.R. Finlen, 1967: The transport of Northwest Providence Channel.*Deep-Sea Res.*, **14**, 361-367.

Roemmich, D., 1981: Circulation of the Caribbean Sea: A well-resolved inverse problem, *J. Geophys. Res.*, **86**, 7993-8005.

Schott, F.A., T.N. Lee and R. Zantopp, 1988: Variability of structure and transport of the Florida Current in the period range of days to seasonal. J. Phys. Oceanogr., 18 (9), 1209-1230.

Wallcraft, A.J., 1991: The Navy Layered Ocean Model users guide. NOARL Report 35, Nav. Res. Lab., Stennis Space Center, MS, 21 pp.

Wallcraft, A.J. and D.R. Moore, 1997: The NRL Layered Ocean Model. *Parallel Computing*, **23**, 2227-2242.

Wallcraft, A.J., H.E. Hurlburt, R.C. Rhodes, and J.F. Shriver, 2000: Global and basin scale ocean modeling and prediction. 2000 DoD HPC User Group Conference Proceedings, (published online at the url http://www.hpcmo.hpc.mil/Htdocs/UGC/UGC00).

Wunsch, C. and B. Grant, 1982: Toward the general circulation of the North Atlantic Ocean, *Prog. Oceanography*, **11**, 1-59.

Figure Legends

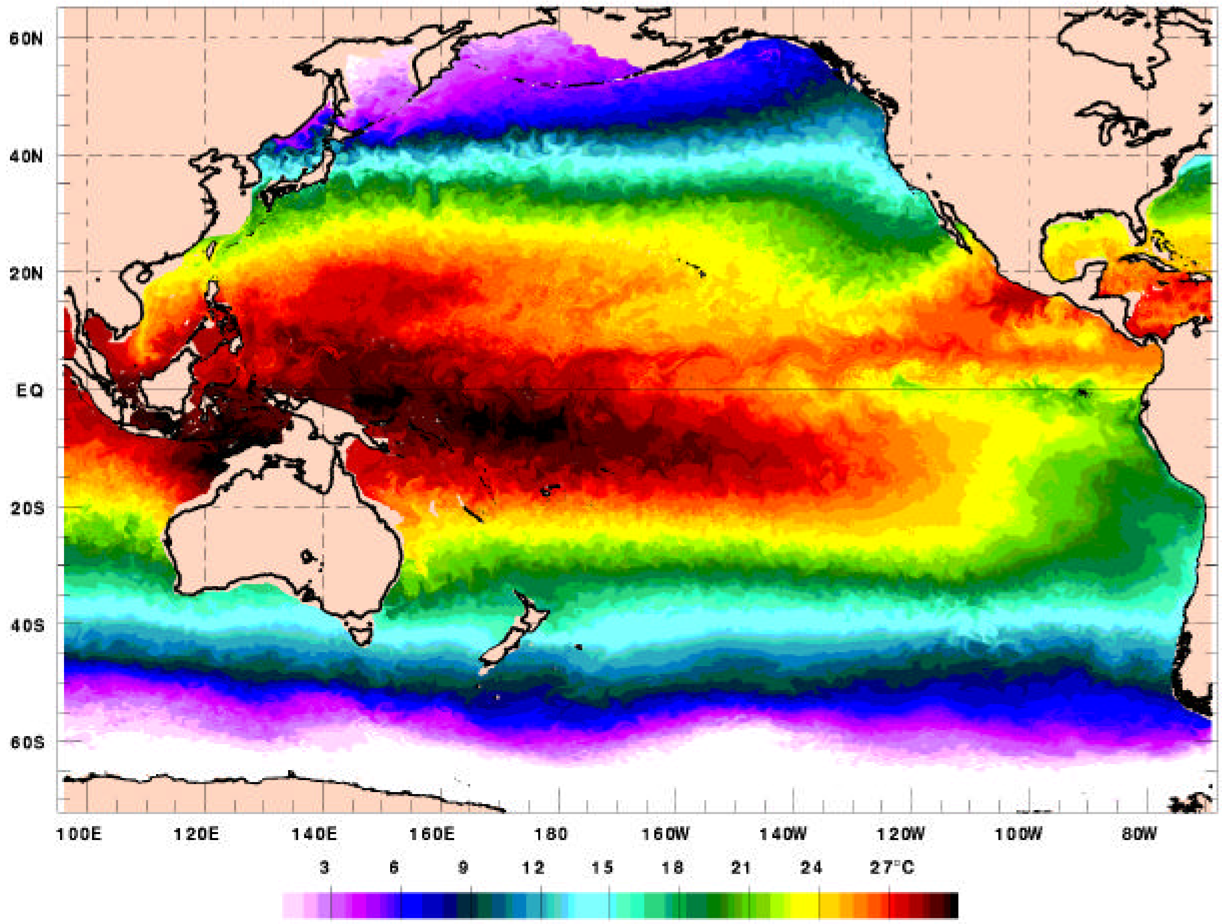

Figure 1. Sea surface temperature (SST) snapshot from the 1/32° global version of NLOM currently running as part of this FY01-03 DoD HPC Challenge project. The date is 2 Dec from year 18 of the climatologically forced 1/32° simulation. The wind stress forcing is the Hellerman and Rosenstein (1983) monthly climatology with a high frequency component added. The thermal forcing is from the COADS monthly climatology (da Silva et al., 1994). There is no relaxation to SST. The model also contains a global thermohaline circulation driven mainly by ports in the far North Atlantic.

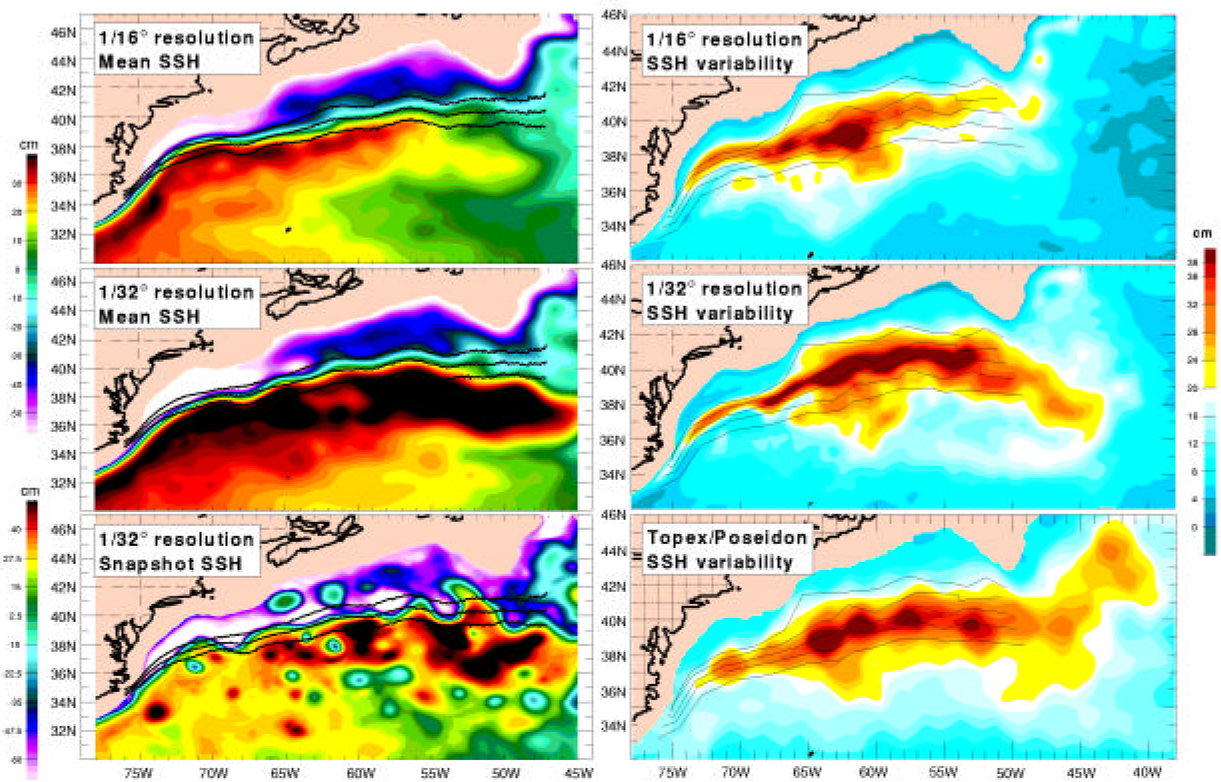

Figure 2. Gulf Stream region results. Comparison of mean sea surface height (SSH) from the 1/16° and 1/32° global models with the observed mean Gulf Stream northwall pathway over 1982-1996 ± standard deviation from satellite IR (Cornillion and Sirkes, personal communication). Snapshot of SSH from the 1/32° global model. Comparison of SSH variability between the 1/16° and 1/32° global models and analysis of Topex/Poseidon data by Jacobs (NRL). The 5 lines overlaid on each SSH variability plot are the Gulf Stream mean axis (center), standard deviation about the mean axis and extreme positions determined from Topex/Poseidon data (Lee et al., 1997).

Table 1. Comparison of Modeled versus Observed Passage Transports in Sverdrups (10^6 m^3/s) in the Caribbean Sea/Bahamas/Gulf of Mexico Region.

Passage	1/16° NLOM Mean	1/32° NLOM Mean	Observed Mean (Std dev, Std err)	Source of Observation
Florida Straits at 27°N	30.1	33.2	32.3 (3.2,-) 31.5 (1.5,-)	Larsen (1992) Lee *et al*. (1996)
NW Providence	4.2	2.4	2 1.2 (2.0,-)	Richardson and Finlen (1967) Leaman *et al*. (1995)
Florida Straits at 25.5°N	25.9	30.8	30	Niiler and Richardson (1973) Schott *et al*. (1988)
Old Bahama	1.3	1.5	1.9 (1.7,-)	Atkinson *et al*. (1995)
Yucatan	24.6	29.6		
Windward	2.4	5	7 9 6.0-7.0	Roemmich (1981) Nelepo *et al*. (1976) Wunsch and Grant (1982)
Mona	2.4	3	2.6 (1.2,1.2)	Johns *et al*. (2001)
Anegada	4.7	4.2	2.5 (1.4,0.6)	Johns *et al*. (2001)
Guadeloupe	3.3	1.4	3.1 (1.5,0.7)	Johns *et al*. (2001)
Dominica	1.2	1.5	1.1 (1.1,0.5)	Johns *et al*. (2001)
Martinique	1.3	1.4	1.6 (1.2,0.5)	Johns *et al*. (2001)
St. Lucia	3.3	1.2	1.5 (2.4,0.8)	Johns *et al*. (2001)
St. Vincent	1.5	4.3	2.9 (2.2,0.8)	Johns *et al*. (2001)
Grenada	4.1	5.1	5.7 (2.4,0.8)	Johns *et al*. (2001)
Sum of last 3	8.9	10.6	10.1 (4.0,2.4)	Johns *et al*. (2001)